THE ELECTRON DENSITY IN THE DIRECTION OF ζ OPH

THEODORE P. STECHER and DAVID A. WILLIAMS
Goddard Space Flight Center, NASA, Greenbelt, Md., U.S.A. and
Mathematics Department, U.M.I.S.T., Manchester, England

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Abstract. It is shown that photoionization of vibrationally excited H₂ and photodissociation of the H₂⁺ ions produced thereby constitute a significant electron production route in high UV flux situations. A significant fraction of the electron density in the direction of ζ Oph (−15 km s⁻¹ cloud) deduced from observations may be expected to arise in this way.

The density of electrons in interstellar clouds in the directions of certain stars has been calculated from measurements of Ca I and Ca II absorption (White, 1973; Bortolot et al., 1974). In the ζ Oph −15 km s⁻¹ cloud the electron density n(e) is found to be in the range 0.16–0.55 cm⁻³. Taking account of measurements of hydrogen atom and molecule densities in this direction (Spitzer et al., 1973), this result implies that even the full relative abundance of carbon can probably not supply this amount of ionization, and therefore that some of the hydrogen must be ionized. Further, there is evidence of depletion of carbon by a factor of about ten in this direction (Morton et al., 1973) and so the problem is made more acute. This paper offers at least a partial solution.

We have recently stressed the importance of vibrationally excited molecular hydrogen (H₂⁺) in some processes in the interstellar medium (Stecher and Williams, 1972, 1973, 1974a). Another interesting possibility is that H₂⁺ (v''>4) can be photoionized by photons available in neutral regions. Since two photons are required, one to excite H₂⁺ (v''>4) in an X→B→X transition (Stecher and Williams, 1967), and one to photoionize H₂⁺, this mechanism will clearly be most significant for regions of high ultra-violet intensity.

A model which can explain the CH and CH⁺ observations in the (−15 km s⁻¹) cloud in the direction of ζ Oph is available (Stecher and Williams, 1974b). In this model, the cloud containing n(H)≈n(H₂)≈100 cm⁻³ is situated about R₀=1 pc from the star, which is rapidly approaching the cloud (velocity ∼30 km s⁻¹). In such a situation the flux F₀ at the edge of the cloud is much greater than the mean interstellar flux. vibrationally excited H₂ has been sought in the ζ Oph cloud but not found (Spitzer et al., 1974). The upper limit for H₂⁺, v''=1, J=0 is 2.4×10⁻⁸ of the H₂, v''=0 column density. Using an analytic fit for the equivalent widths from Cartwright and Drapatz (1970) and taking account of excitation in all the Lyman bands of H₂ we find, ignoring extinction, that the total number density of H₂⁺ (all v'', all J) is

\[ n(H₂⁺, R) = 4 \times 10^{-3} F(R) \frac{\sqrt{n(H₂)}}{R - R₀} \text{ cm}^{-3}, \quad R > R₀, \]

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at position \( R \) in the cloud. We shall later assume that only one half of this \( H^* \) is sufficiently excited (i.e. \( v^* > 4 \)) for photoionization to occur. We calculate the flux on the basis of Morton’s (1965) model of a B0 star of radius 10 \( R_\odot \) and find \( F_0 = F(R_0) = 10^7 \) photons cm\(^{-2}\) s\(^{-1}\) \( \text{Å}^{-1} \) in the wavelength range around 1000 \( \text{Å} \). Using \( n(H_2) = 100 \) cm\(^{-3}\), the mean value of \( n(H^*_2) \) for the whole cloud is \( 3 \times 10^{-6} \) cm\(^{-3}\), equivalent to \( 3 \times 10^{-8} n(H_2) \). Since this \( H^*_2 \) is distributed over all vibrational and rotational levels, this result is certainly not in conflict with the negative observation of Spitzer et al. (1974).

As indicated in the discussion of Dalgarno et al. (1973), electrons produced by cosmic ray ionization of \( H_2 \) to \( H^+_2 + e \) are extremely rapidly lost in dissociative recombination with the \( H_2^+ \) which is formed immediately from \( H_2^+ + H_2 \). Those authors suggest, therefore, that the significant electron source is the less frequent cosmic ray dissociative ionization of \( H_2 \) to \( H^+ + H + e \), and that these electrons are lost only in the relatively slow process of radiative association with protons. We remark:

(i) that photoionization of \( H^*_2 \) \( (v^* > 4) \) is fast in high intensity situations, so this contributes to the density of \( H^+_2 \) and electrons, and (ii) that another route by which \( H^+_2 \) is lost is photodissociation, and each photodissociation effectively increases the electron density, because electrons associated with this route do not recombine with \( H_3^+ \). Therefore, \( H^*_2 \) \( (v^* > 4) \) can contribute to the electron density.

We solve the equations corresponding to the following reactions

\[
\begin{align*}
H + \text{cosmic rays} & \rightarrow H^+ + e, & \text{rate } 0.6 \zeta, \\
H_2 + \text{cosmic rays} & \rightarrow H_2^+ + e, & \text{rate } 0.95 \zeta, \\
H_2 + \text{cosmic rays} & \rightarrow H + H^+ + e, & \text{rate } 0.05 \zeta, \\
H^*_2 + hv & \rightarrow H_2^+ + e, & \text{rate } \beta_1, \\
H^+_2 + hv & \rightarrow H + H^+, & \text{rate } \beta_4, \\
H_2^+ + H_2 & \rightarrow H_3^+ + H, & \text{rate coefficient } k_1, \\
H^+_2 + e & \rightarrow H_2 + H, \text{ or } 3H, & \text{rate coefficient } k_2, \\
H^+_2 + e & \rightarrow H, & \text{rate coefficient } k_3.
\end{align*}
\]

We adopt a cosmic ray ionization rate \( \zeta = 10^{-17} \) s\(^{-1} \) (Spitzer and Tomasko, 1968); \( \beta_1 \) may be calculated from the work of Cook and Metzger (1964) and \( \beta_4 \) from the work of Dunn (1968). The rate coefficients are \( k_1 = 2 \times 10^{-9} \) cm\(^3\) s\(^{-1} \) (Bowers et al., 1969), \( k_2 = 3 \times 10^{-7} \) cm\(^3\) s\(^{-1} \) (Leu et al., 1973) and \( k_3 = 1 \times 10^{-11} \) cm\(^3\) s\(^{-1} \) (Allen, 1963).

In equilibrium, we find with Dalgarno et al. (1973) that \( n(e) \approx n(H^+) \), and assuming this approximate equality is exact, we obtain for \( n(e) \) the expression

\[
k_3 n^2(e) = \frac{\beta_4}{\beta_4 + k_1 n(H_2)} [\beta_1 n(H^*_2) + 0.95 \zeta n(H_2)] + 0.6 \zeta n(H) + 0.05 \zeta n(H_2).
\]

This is readily interpreted. The right-hand side represents the rate of production of